Production and detection of tau neutrinos from accelerator sources in DUNE

Pedro Machado, for the DUNE collaboration

NuTau 2021

September 29th, 2021

Why tau neutrinos?

Arguably the least understood particle of the standard model

About couple dozen tau neutrinos identified at DONuT and OPERA
0711.0728, 1804.04912

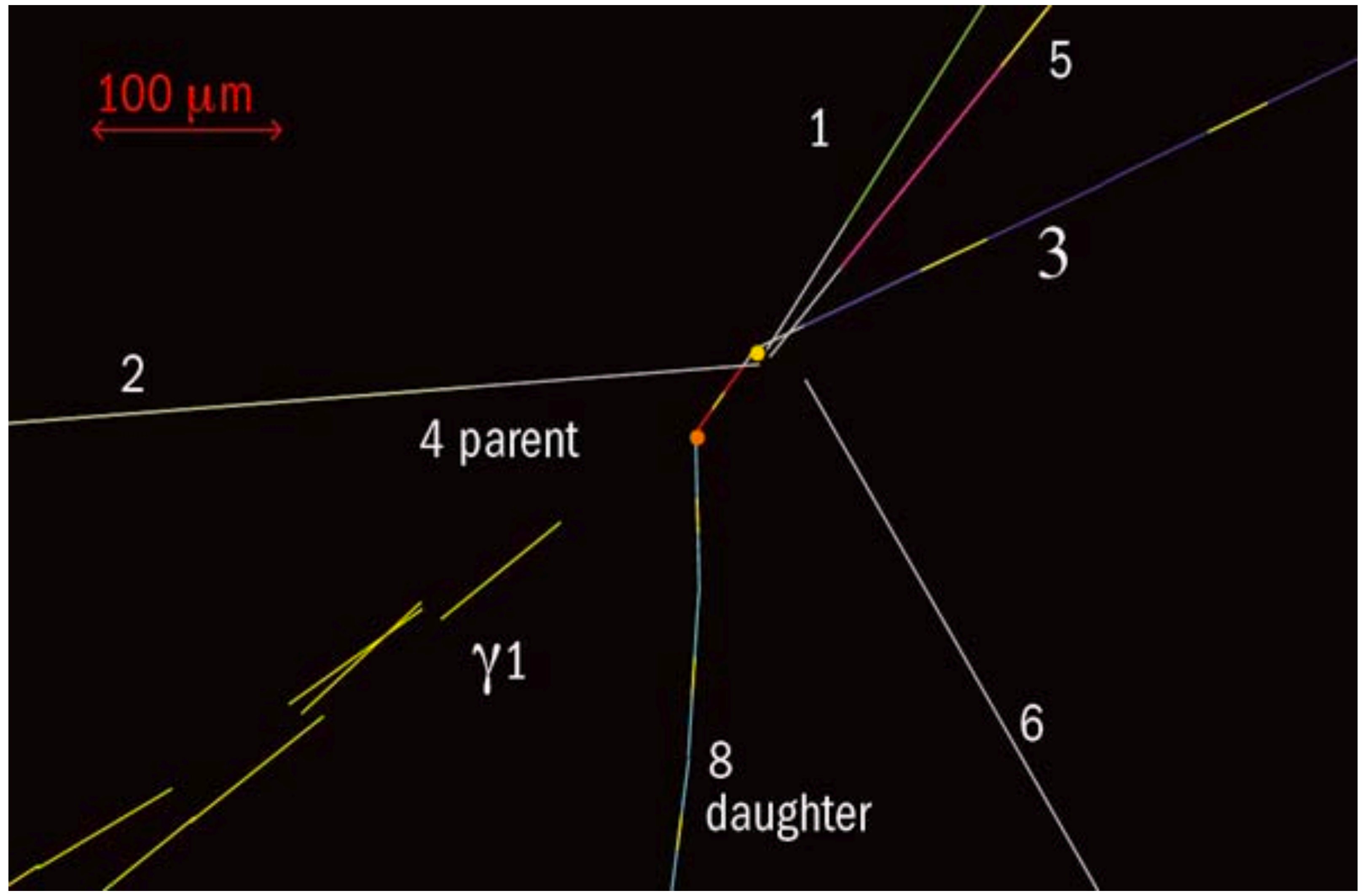
Statistically inferred to be present at Super-Kamiokande and IceCube
1206.0328, 1711.09436, 1901.05366

Production:
1) In the beam via D_s meson decays
2) In far detectors via oscillations (at least $\sin^2 2\theta_{23}$ is large!)

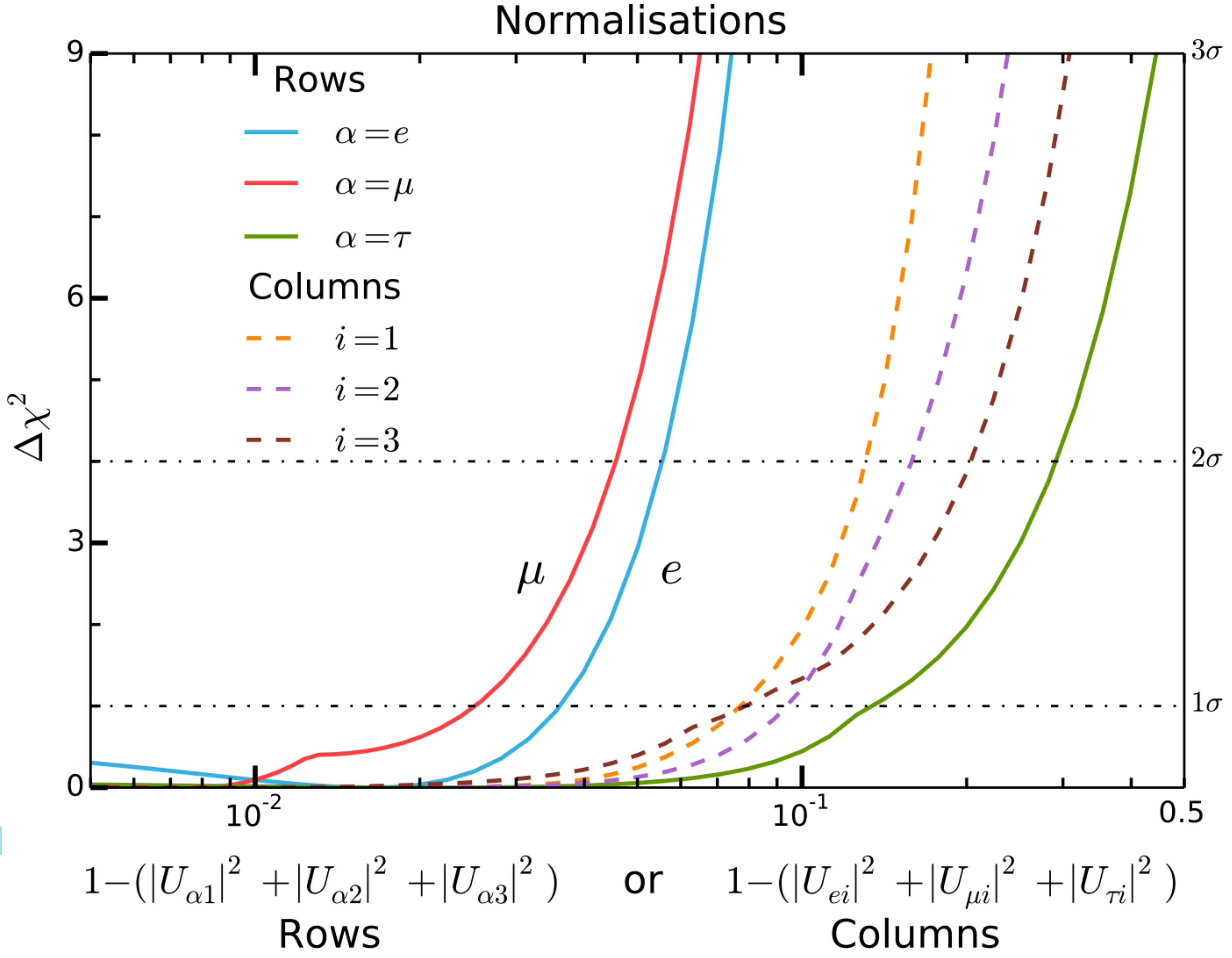
For atmospherics, see Adam's talk

Difficulties:
1) Beam production is suppressed and has large uncertainties
2) Production via oscillations is hard. Minimum E threshold is about 3.5 GeV. Because of Δm^2_{31} value or we move away from the oscillation maximum, losing ν_τ flux, or we go way over 1000 km…

Current knowledge:
1) ν_τ CC cross section @ SK determined at the 21% precision
2) Unitarity of tau row in PMNS at 30% level (@95% CL)



OPERA



Parke Ross-Lonergan 1508.05095

Why tau neutrinos at DUNE?

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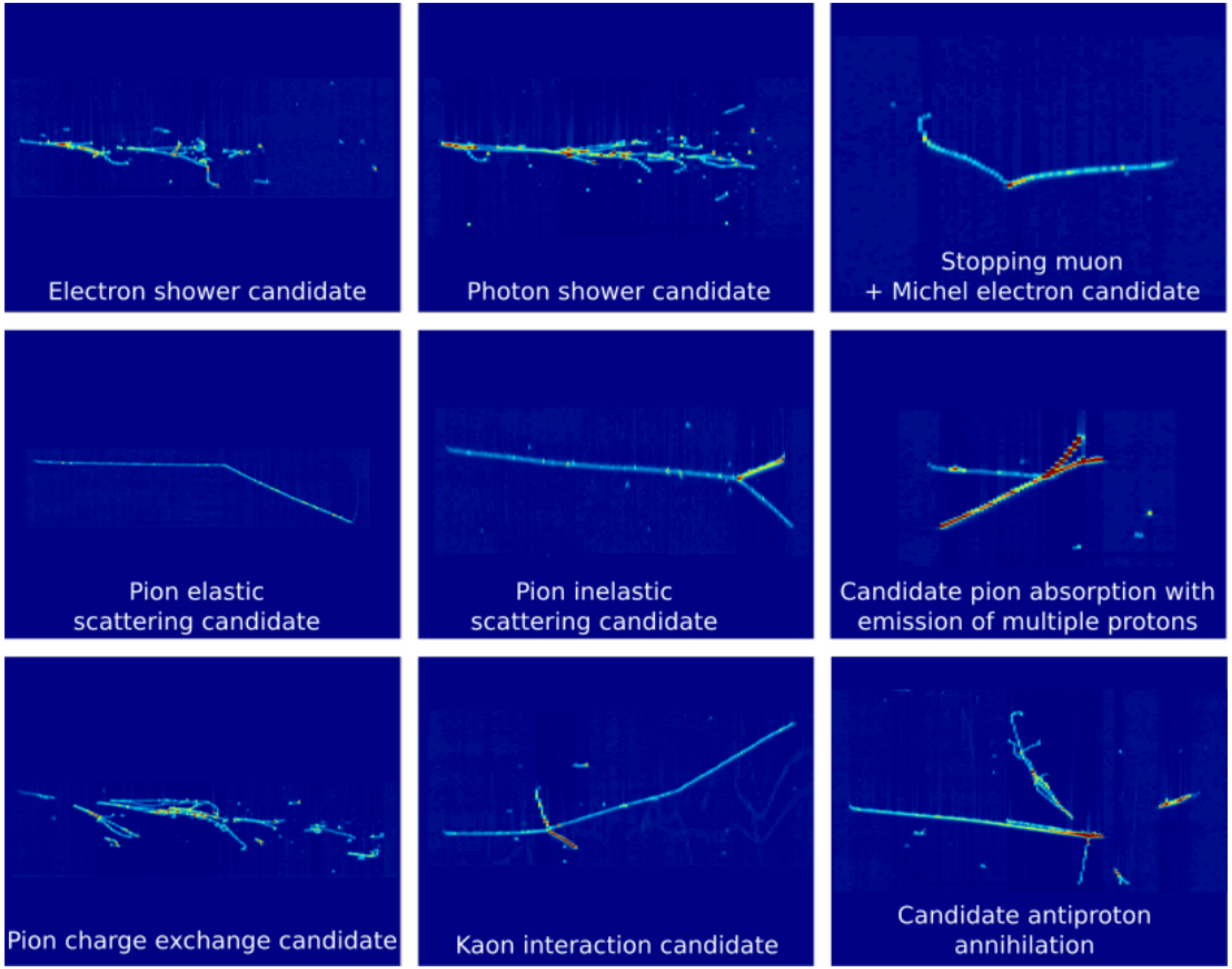
Why tau neutrinos at DUNE?

Topological capabilities: 3D tracking and calorimetry



LArIAT 1911.10379

Muons:

$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$
$\mu^- p^+ \rightarrow \nu_\mu + n$

Pions:

$\pi^+ n \rightarrow \pi^0 p^+$
$\pi^- p^+ \rightarrow \pi^0 n$

Topology depends on particle and its charge

Can we leverage this to measure tau neutrinos?

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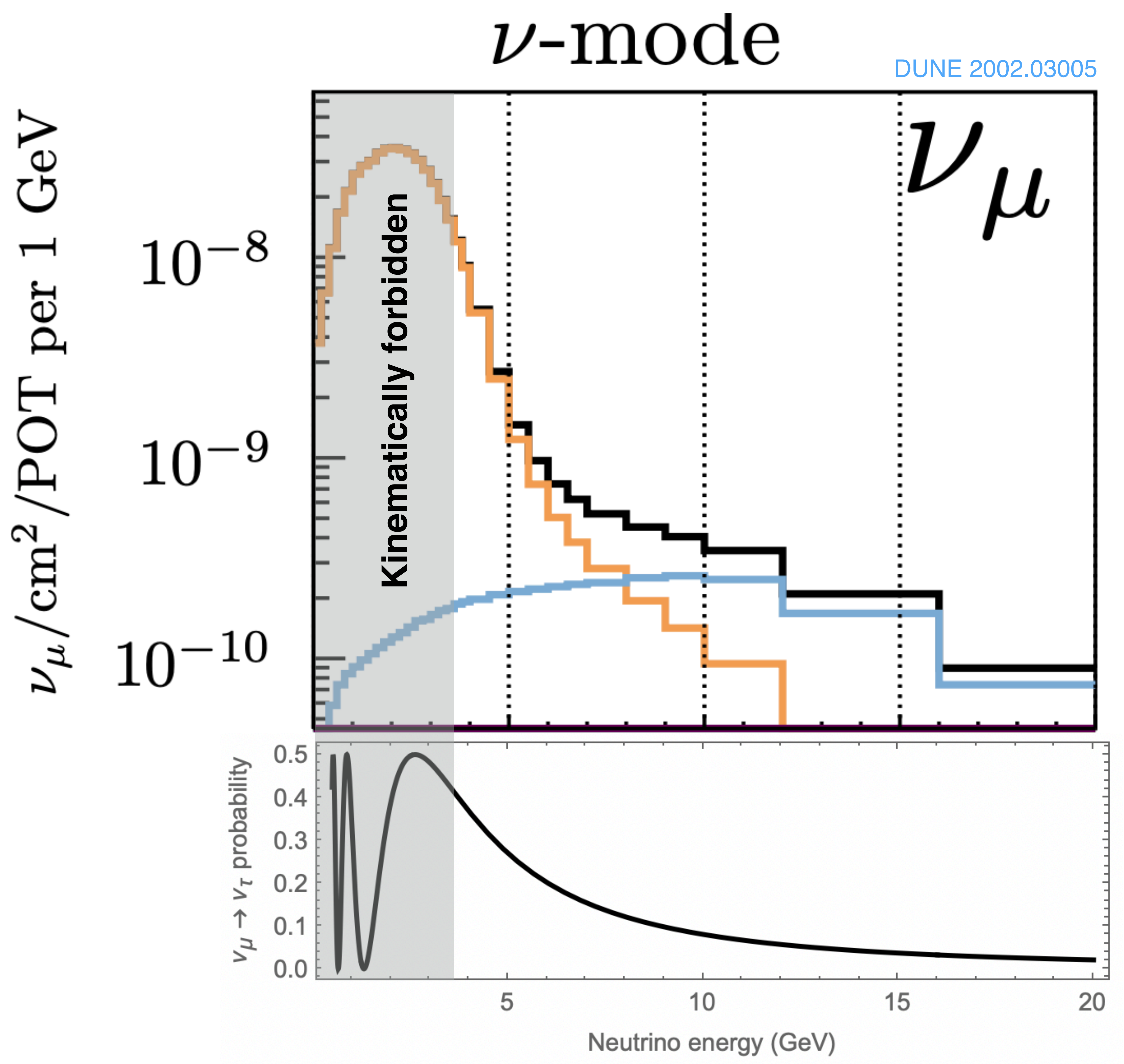
Based on M Schulz Turner 2007.00015
see also
Albright Shrock 1979
NOMAD hep-ex/0106102
Hagiwara et al hep-ph/0408212
Aoki et al hep-ph/0503050
Conrad et al 1008.2984
...

τ lifetime of is too short for DUNE (cτ = 87μm versus mm wire distance)



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Tau reconstruction at DUNE

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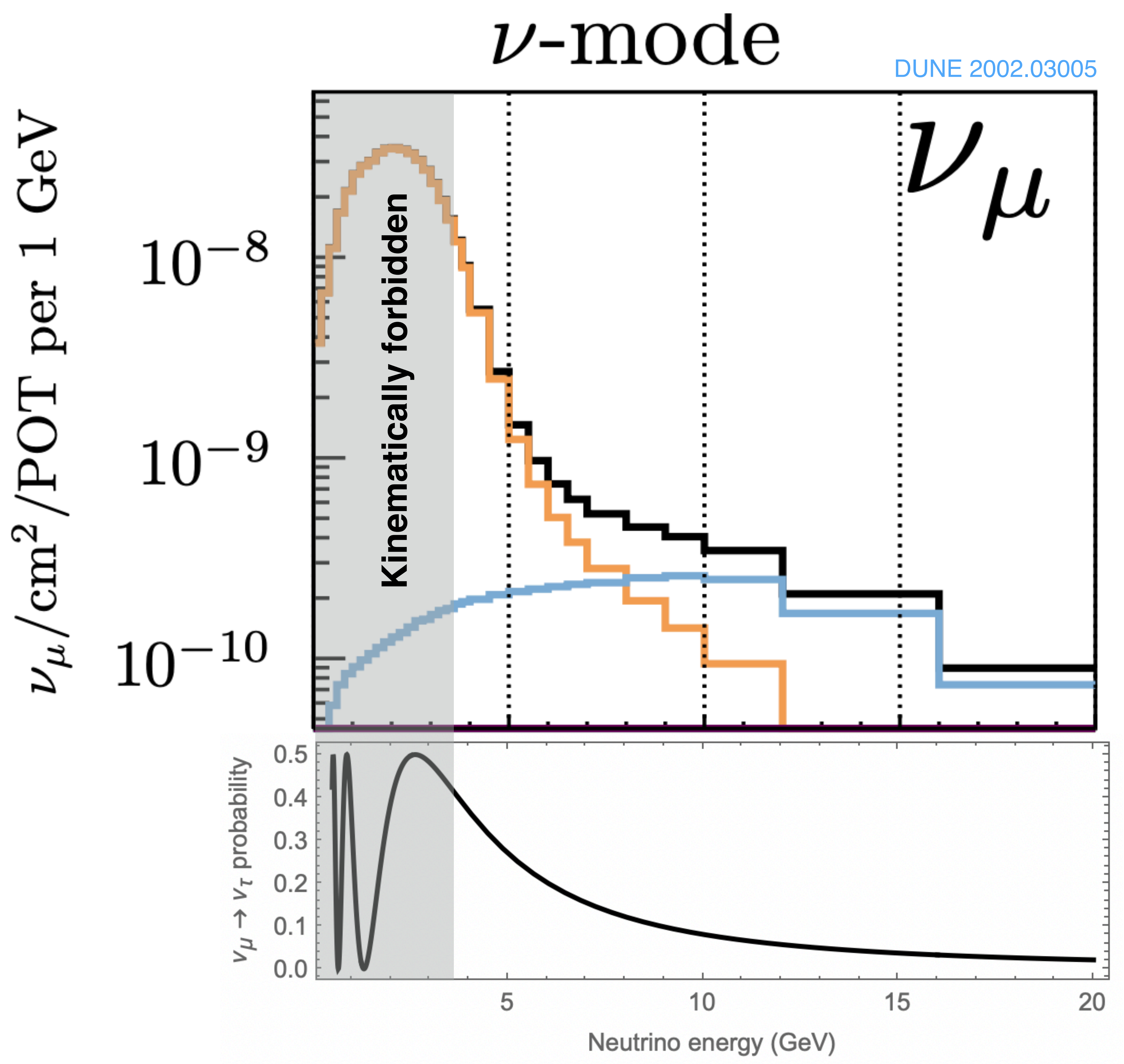
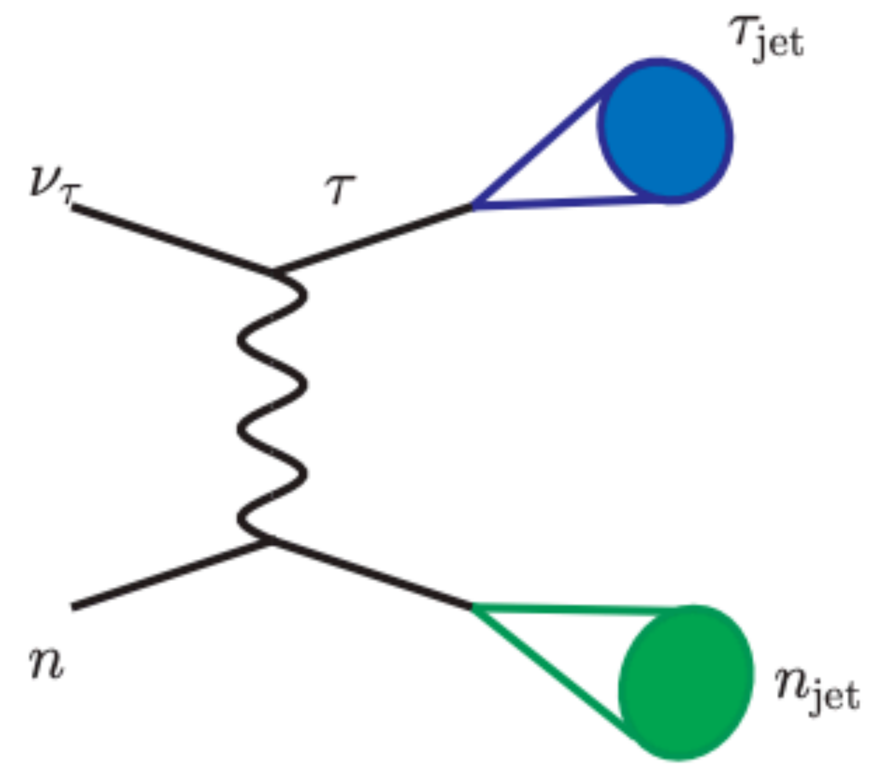
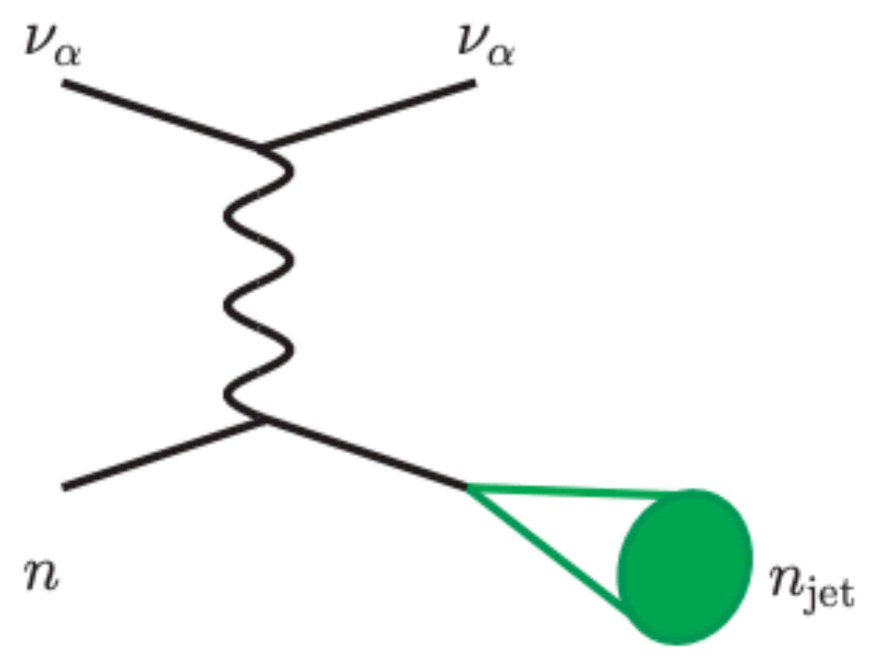


Decay mode	Branching ratio
Leptonic	35.2%
$e^-\bar{\nu}_e\nu_\tau$	17.8%
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
Hadronic	64.8%
$\pi^-\pi^0\nu_\tau$	25.5%
$\pi^-\nu_\tau$	10.8%
$\pi^-\pi^0\pi^0\nu_\tau$	9.3%
$\pi^-\pi^-\pi^+\nu_\tau$	9.0%
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$	4.5%
other	5.7%



Hadronic tau signal



Hadronic tau background (all neutrinos contribute!)

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Tau reconstruction at DUNE

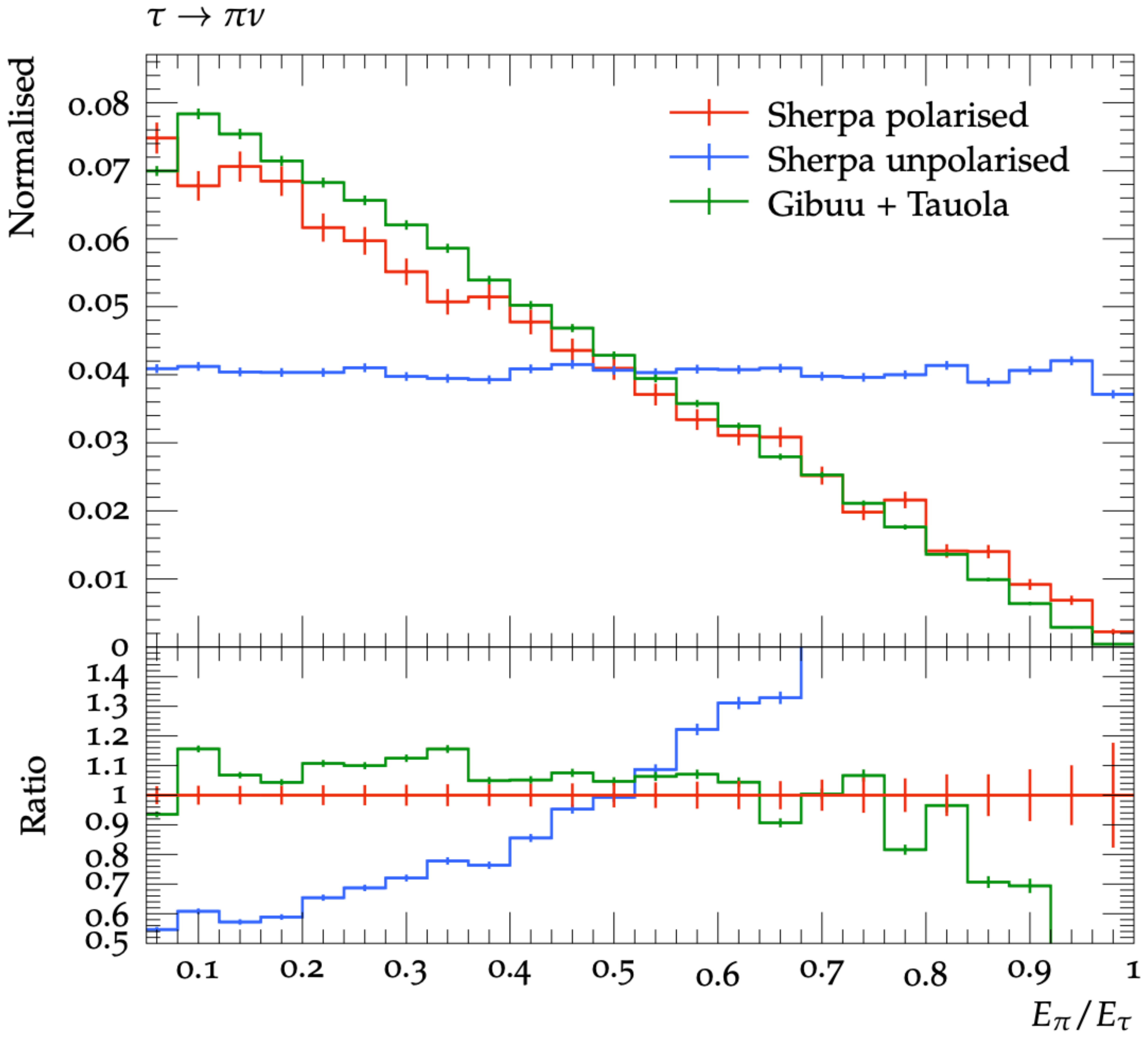
Based on M Schulz Turner 2007.00015

To do this study, we have interfaced GiBUU with TAUOLA to account for the tau polarization.

The analysis was performed with Rivet, which is an analysis framework widely used by the LHC community.

Thresholds for particle detection were 100 MeV for pions, 50 MeV for protons, 30 MeV for photons, electrons and muons (based on DUNE CDR).

We have **not** performed a full fledged detector simulation. This may be particularly relevant for the reconstruction of higher energy pions, which may re-interact before stopping.



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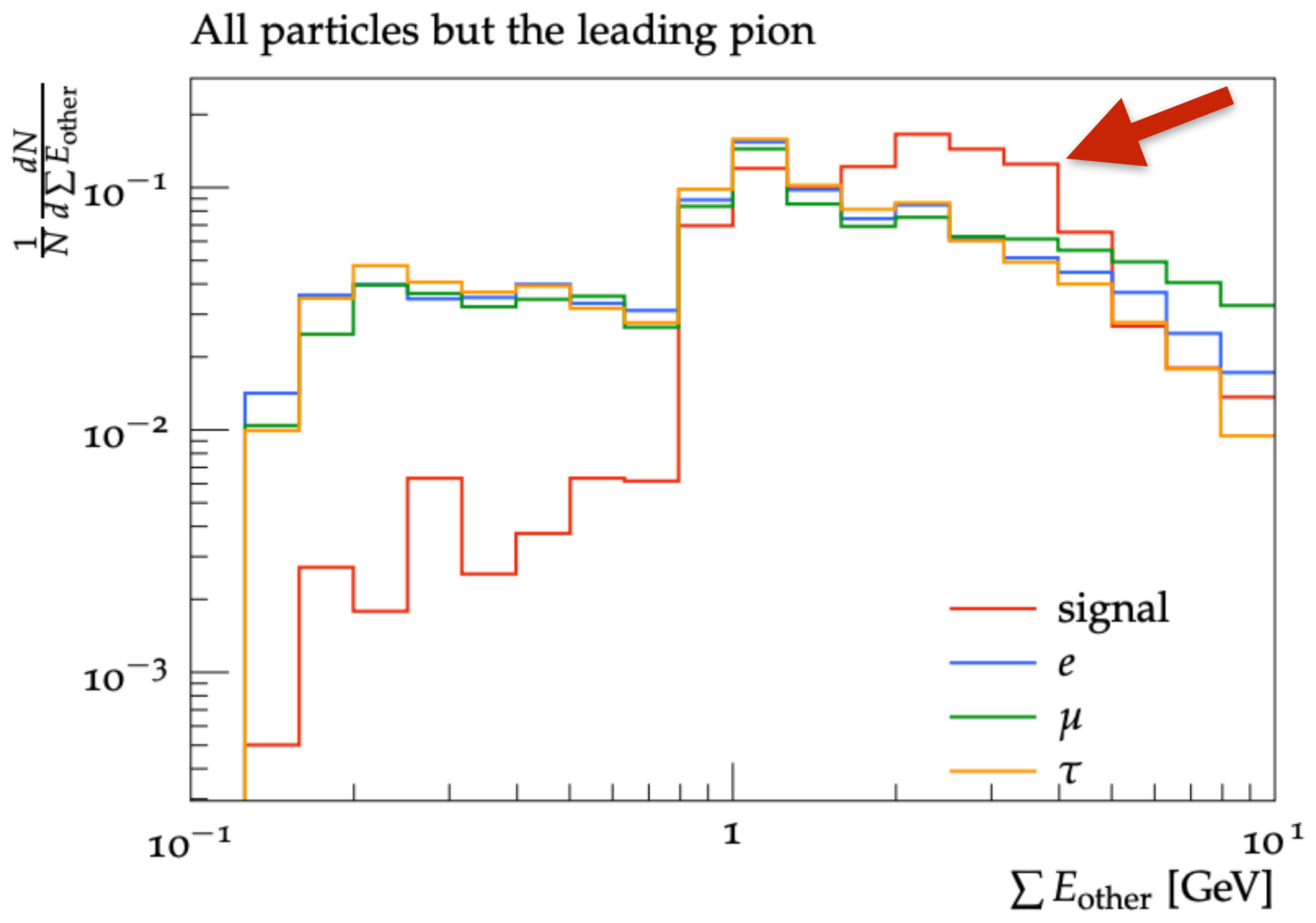
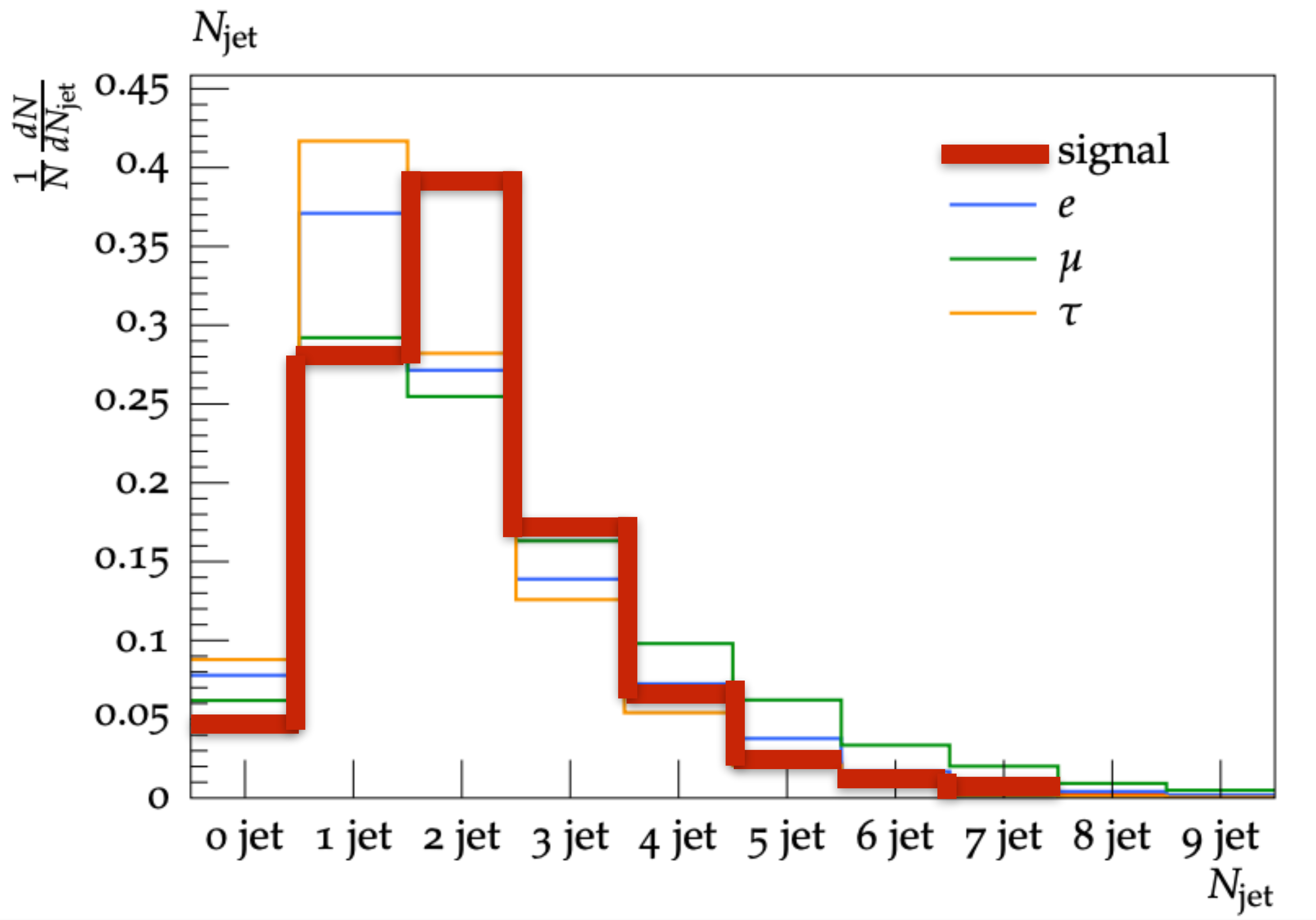
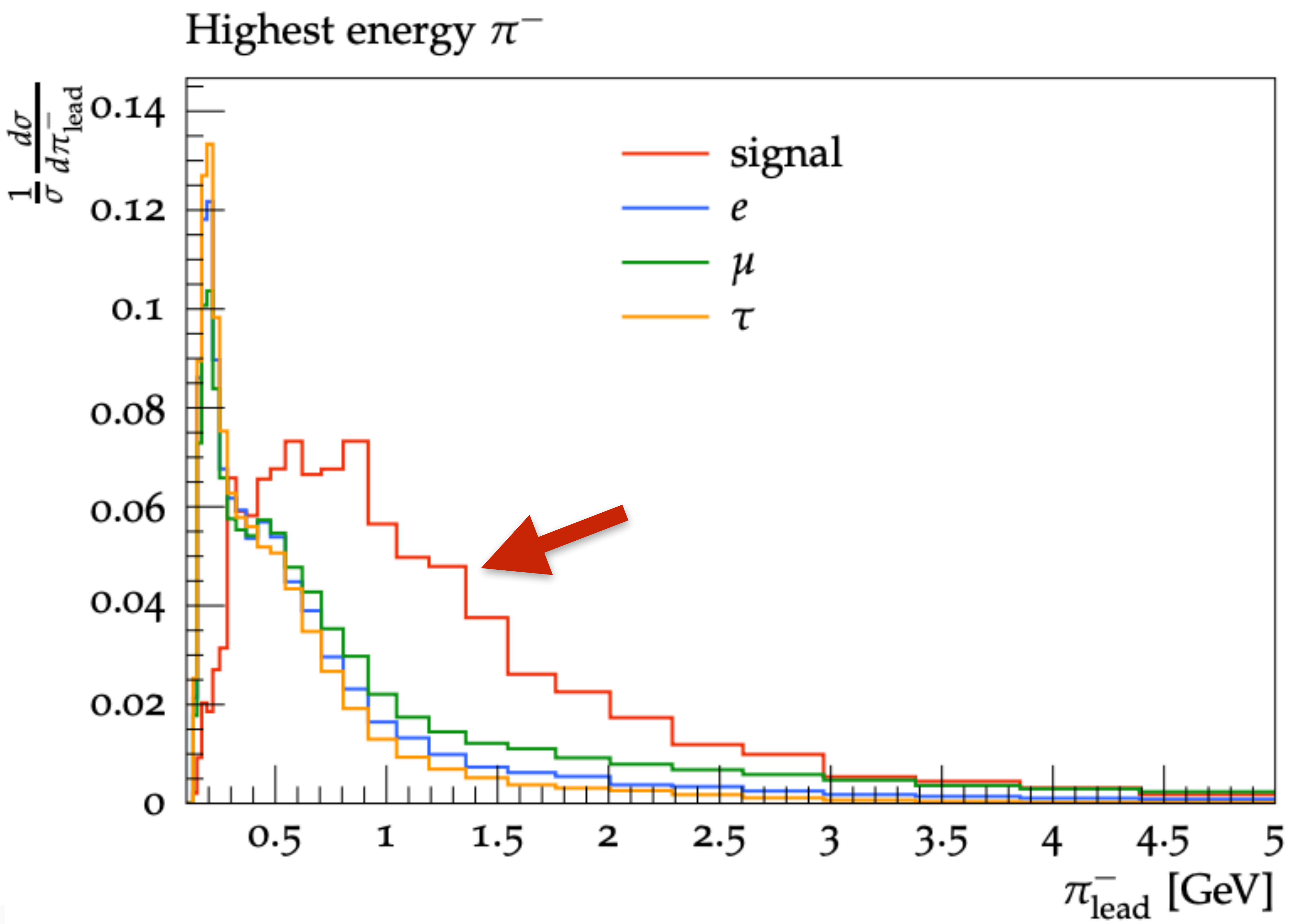


Hadronic taus

Perform a cut and count analysis taking into account

1. Number of leptons = 0
2. Number of pions
3. Energy of leading pion
4. Total visible energy excluding leading pion
5. Missing p_T
6. Number of jets





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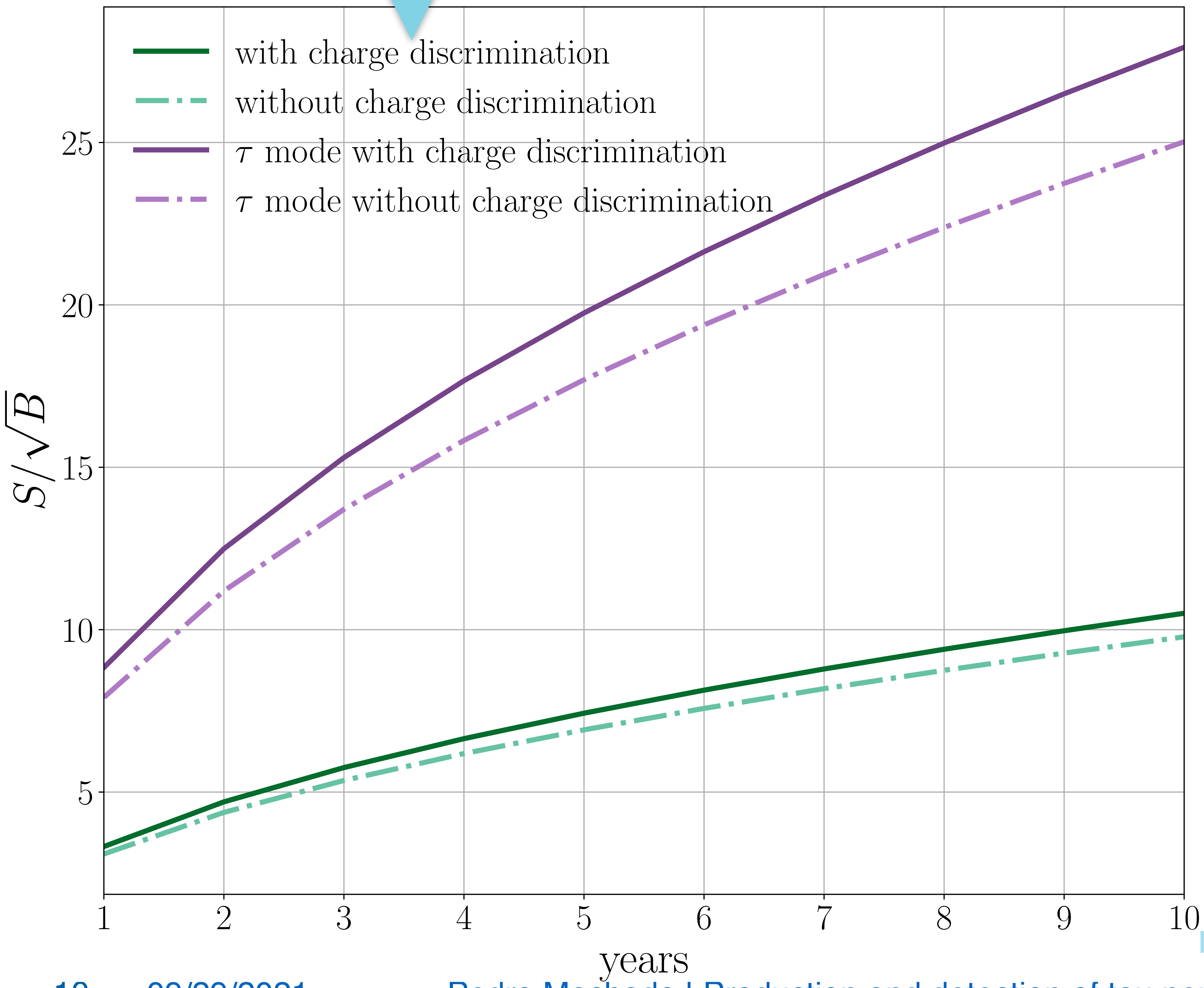
(3.5 yr) x (1.2 MW) x (40 kt) = 168 kt-MW-yr which is equivalent to half of 7 years staged plan
1 year in tau-optimized beam run is quite significant

Hadronic taus



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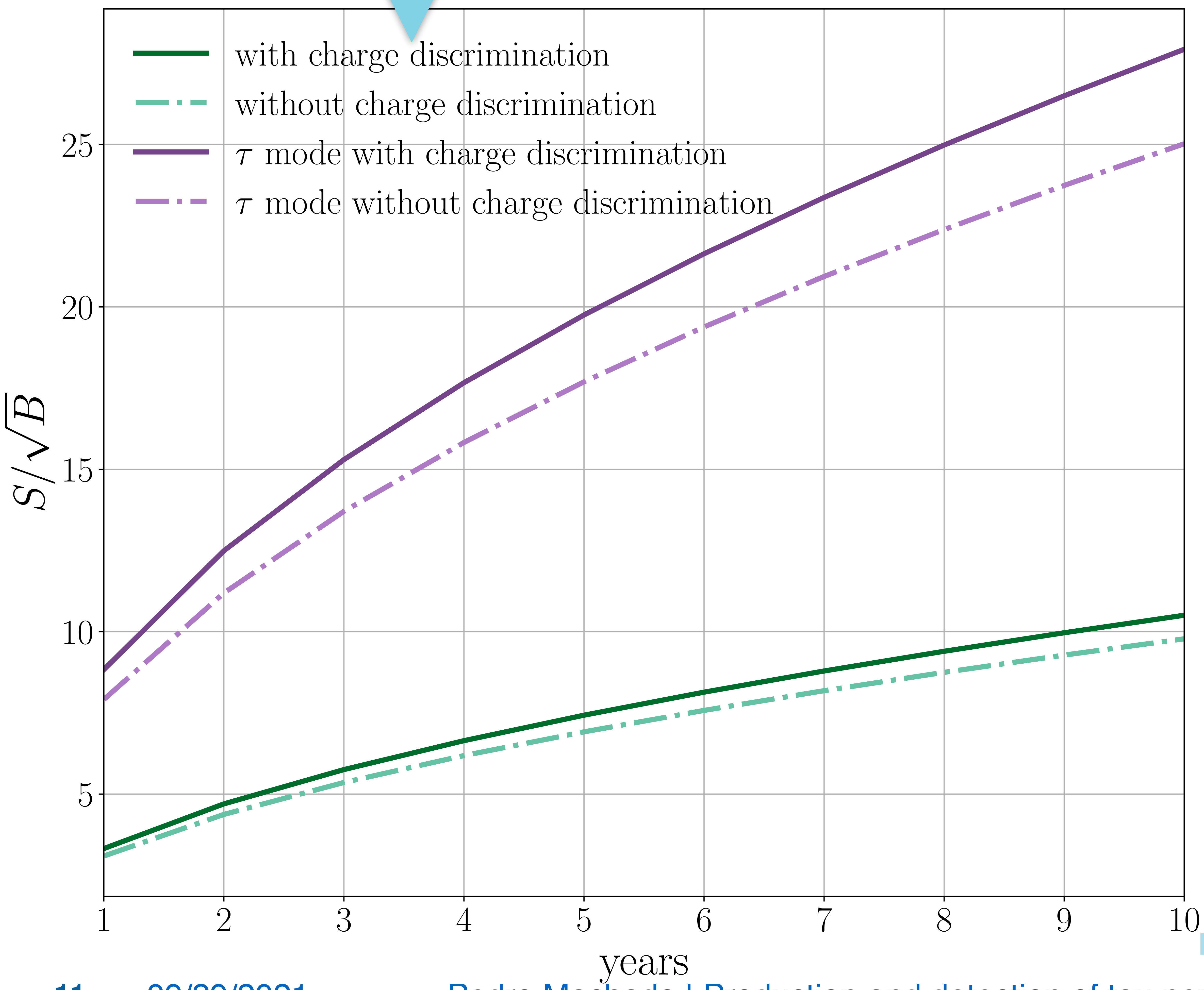

For "electronic tau," things get more complicated, we could not find good cuts by hand for the CP-optimized beam.

We decided to run it through a Deep Neural Network approach.

(See also Miriama's talk for tau search optimization.)

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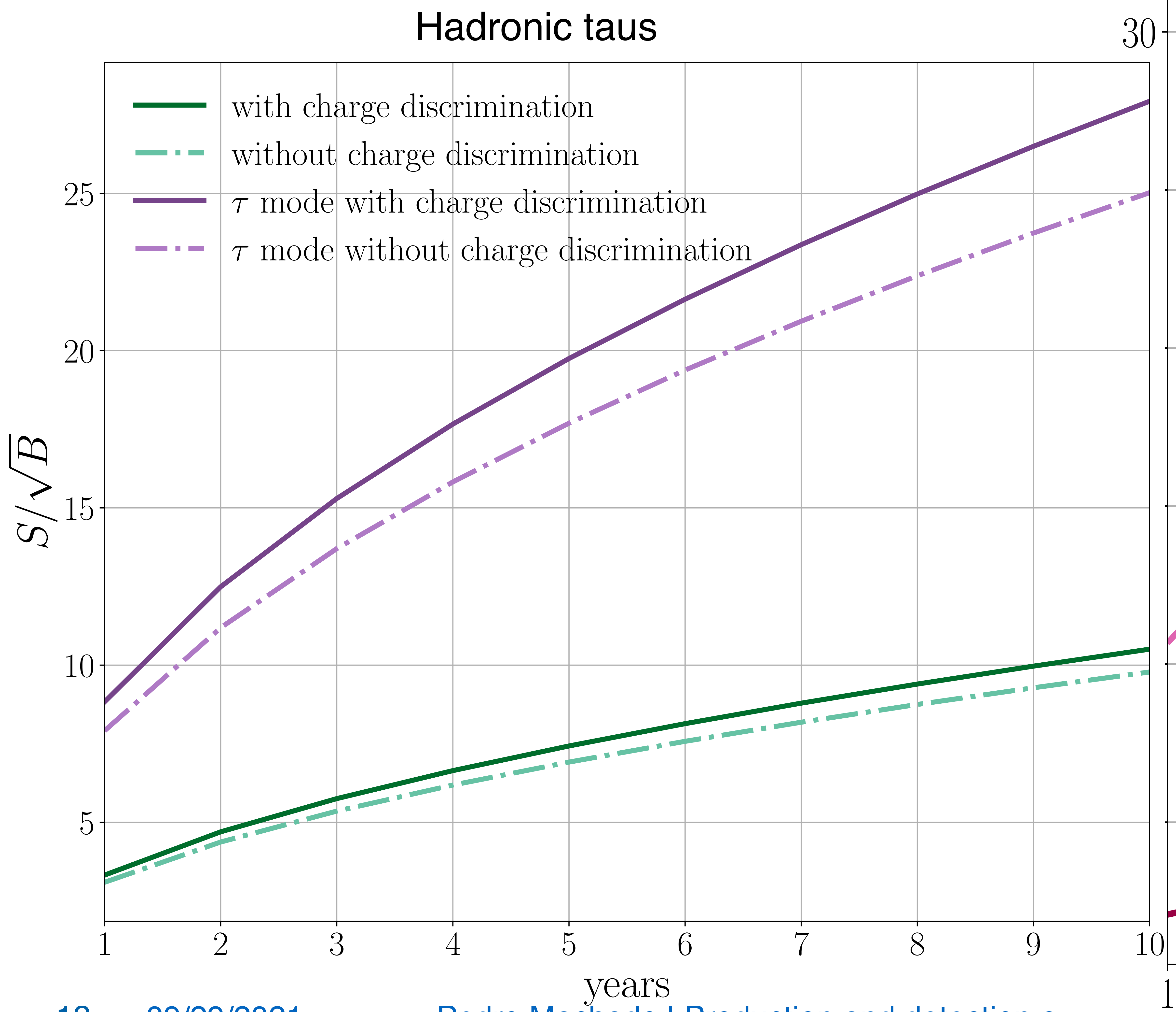

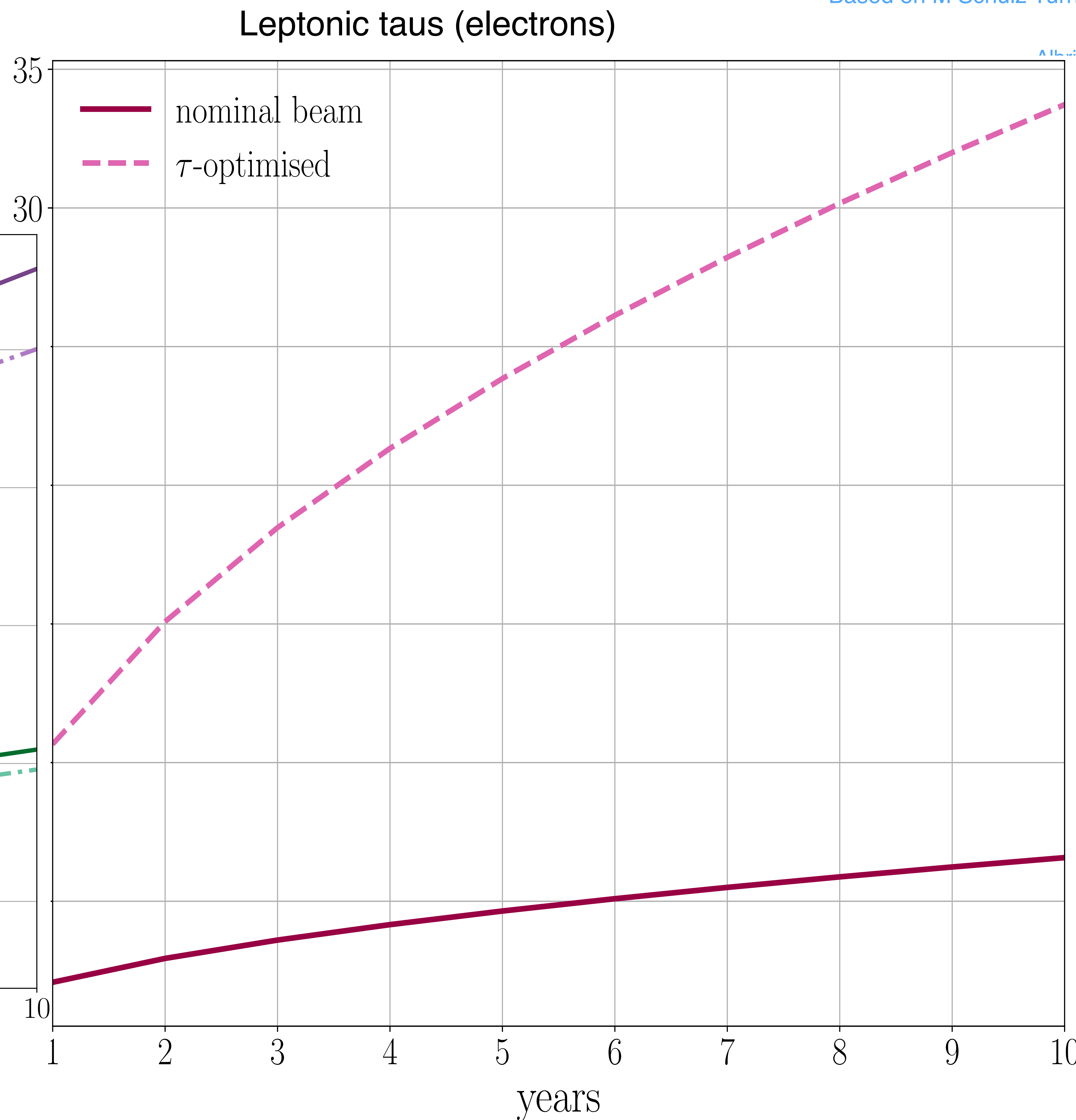

See more on Thomas' talk

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Events after cuts (40 kton, 1 year, 1.2 MW)

Mode	beam	charge id	N_{sig}	N_{bg}	$S/\sqrt{B}$
τ_{had}	nominal	✓	79	565	3.3
τ_{had}	nominal	✗	83	731	3.1
τ_{had}	tau-optimized	✓	433	2411	8.8
τ_{had}	tau-optimized	✗	439	3077	7.9
τ_e	tau-optimized	✗	63	33	11.0
τ_e	nominal	✗	13	32	2.3

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Tau reconstruction at DUNE

What about tau neutrinos
at the near detector?

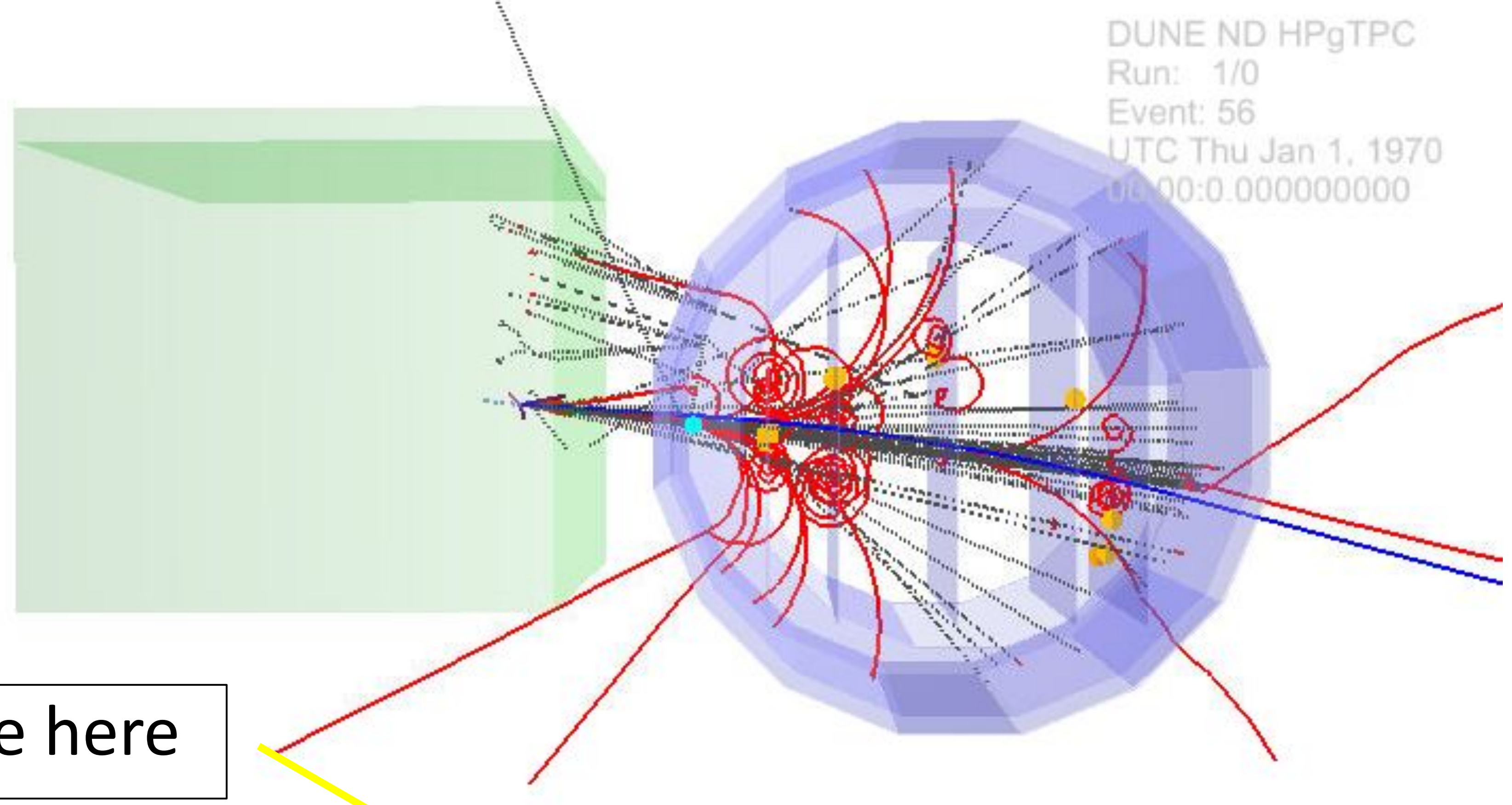
Main complication may arrive from pion reconstruction, as HE pions can re-interact and may not be contained

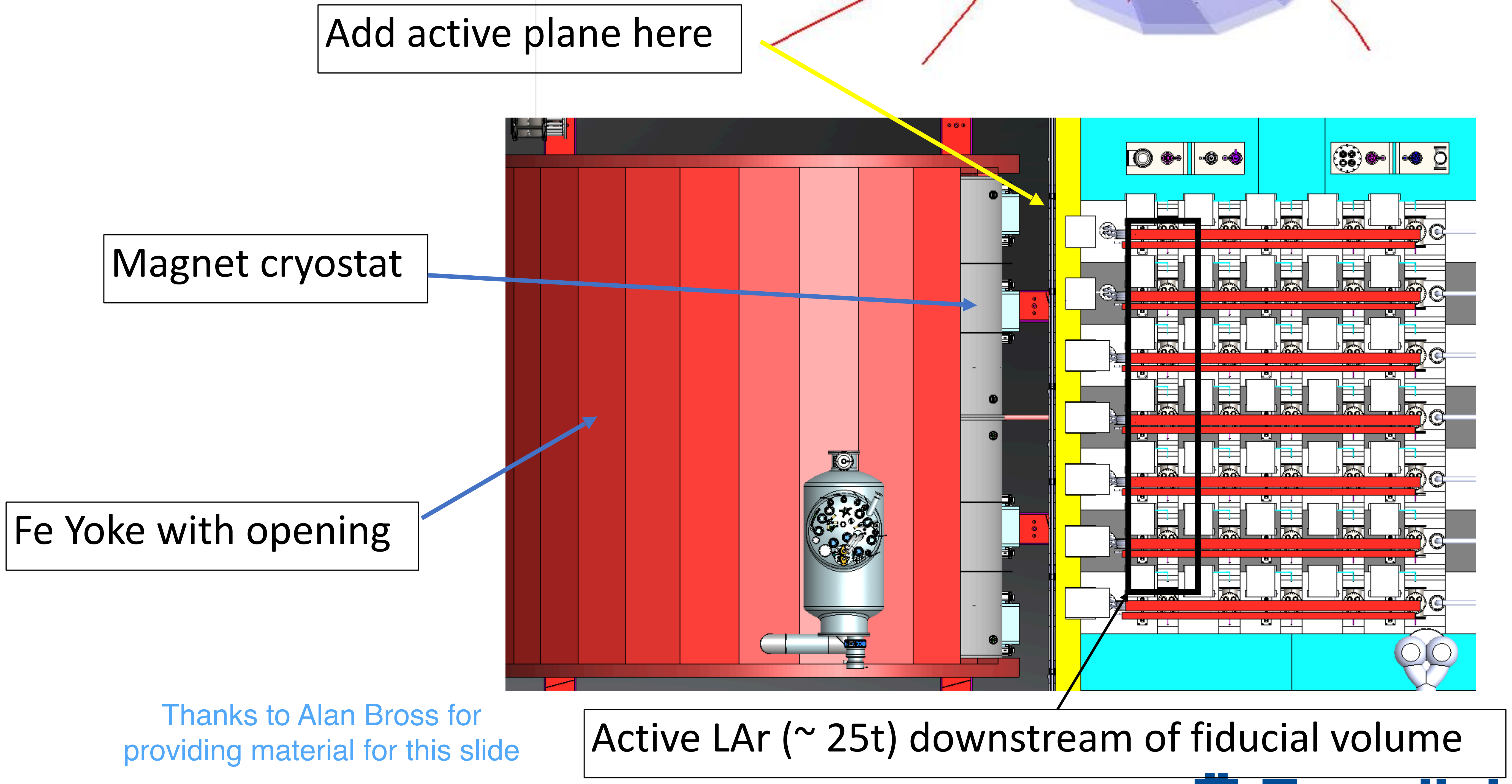
Nevertheless, if an event occurs in the downstream part of the LAr detector, secondaries will likely not re-interact before reaching the ND-GAr detector, where they can be reconstructed with charge and particle ID

Energy + charge + PID is, in principle, very powerful

Study are needed to assess feasibility here

ND-LAr to ND-GAr-Lite event display with a ~25 GeV neutrino interaction.





Thanks to Alan Bross for providing material for this slide

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Tau reconstruction at DUNE

Take home messages

Leveraging DUNE’s topological capabilities can greatly enhance S/B

The high energy beam configuration offers a valuable opportunity to study tau neutrinos

LHC analysis software can be useful for simple studies, perhaps even after detector simulation

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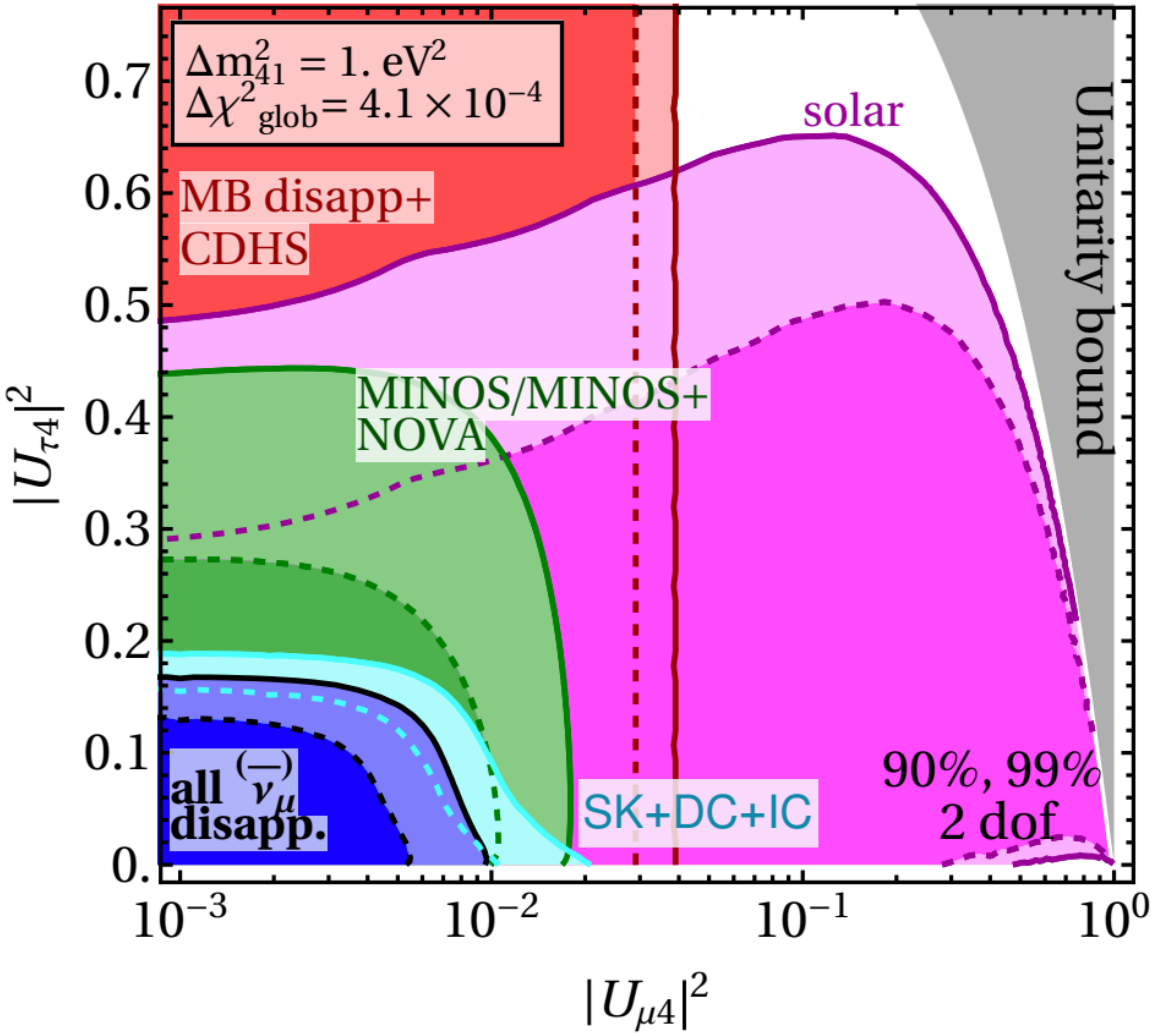
What can we learn with tau neutrinos?

Talks by Kevin, Miriama and Julia will cover this topic in more detail.

Here a few examples: De Gouvea et al 1904.07265

- Light sterile neutrino mixing
- Non-unitarity constraints
- Consistency of three-neutrino oscillations
- Non-standard interactions
- Energy dependent neutrino mixing parameters
- …

Dentler et al 1803.10661



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Conclusions

Combination of massive detector, LArTPC capabilities and high energy beam offers a unique opportunity to study tau neutrinos at DUNE

Preliminary studies accounting for tau polarization and crude detector thresholds show that DUNE could reach signal to background ratios of about 10 or so for 1 year running on tau-optimized beam mode

(Though this needs to be verified in a full detector simulation)

Better understanding of tau neutrino physics can probe several scenarios beyond the standard model, including the origin of neutrino masses

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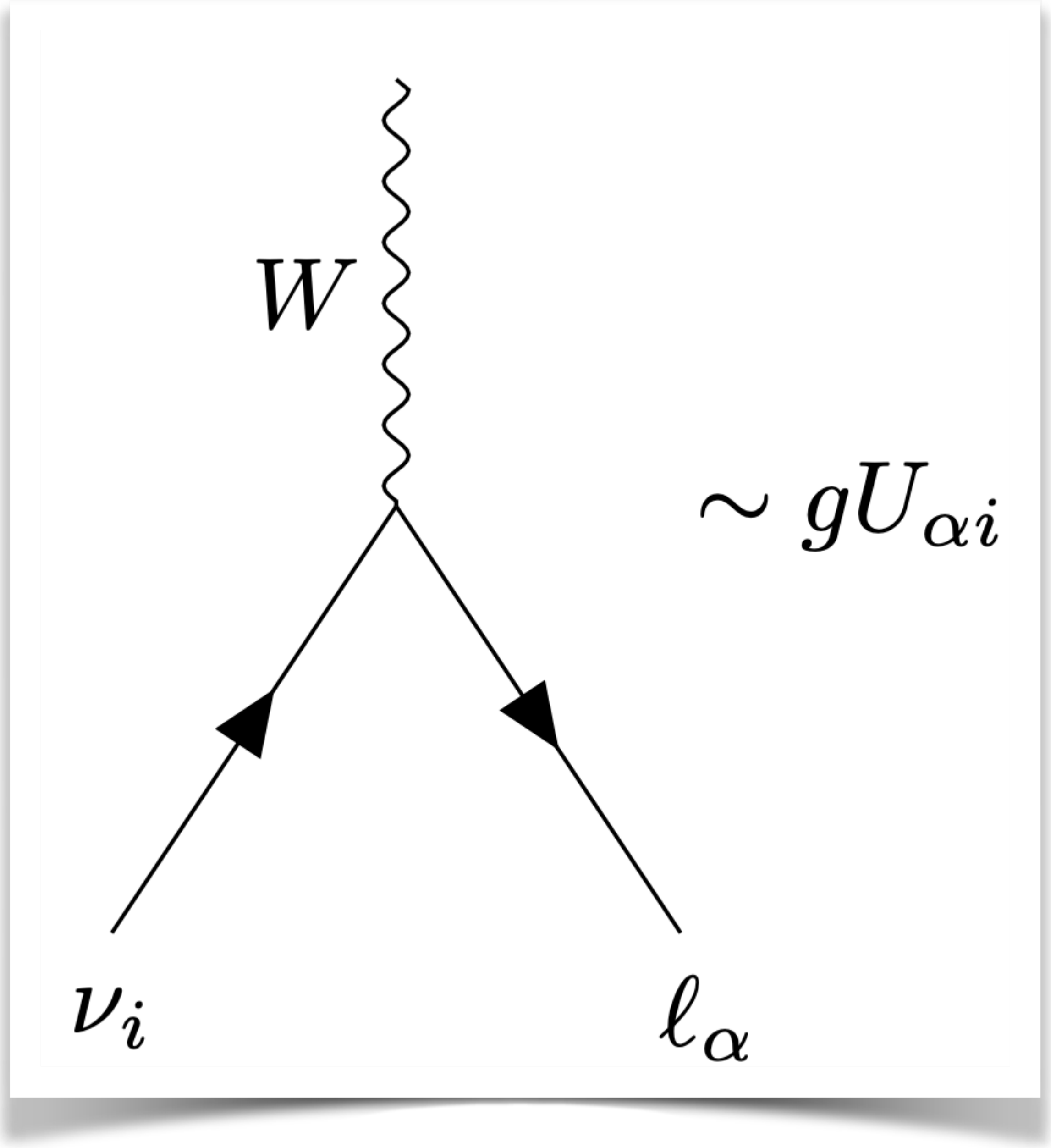
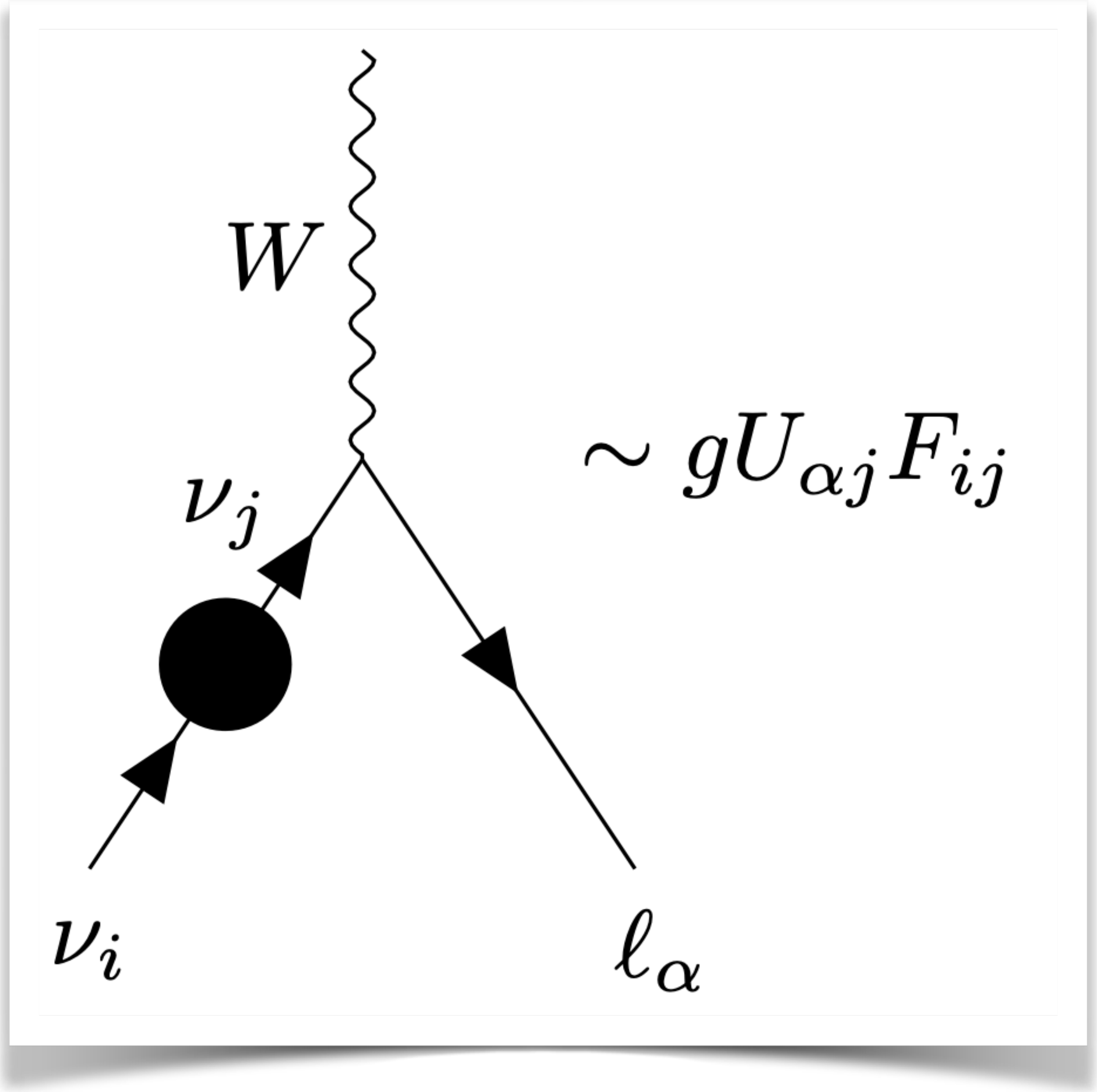
What can we learn with tau neutrinos?

Energy dependent neutrino mixing parameters

Babu et al 2108.11961





If there are significant quantum corrections to the neutrino mass matrix at low scales, the PMNS matrix becomes scale dependent.

This means that production and detection of neutrinos may not go via the same PMNS matrices.

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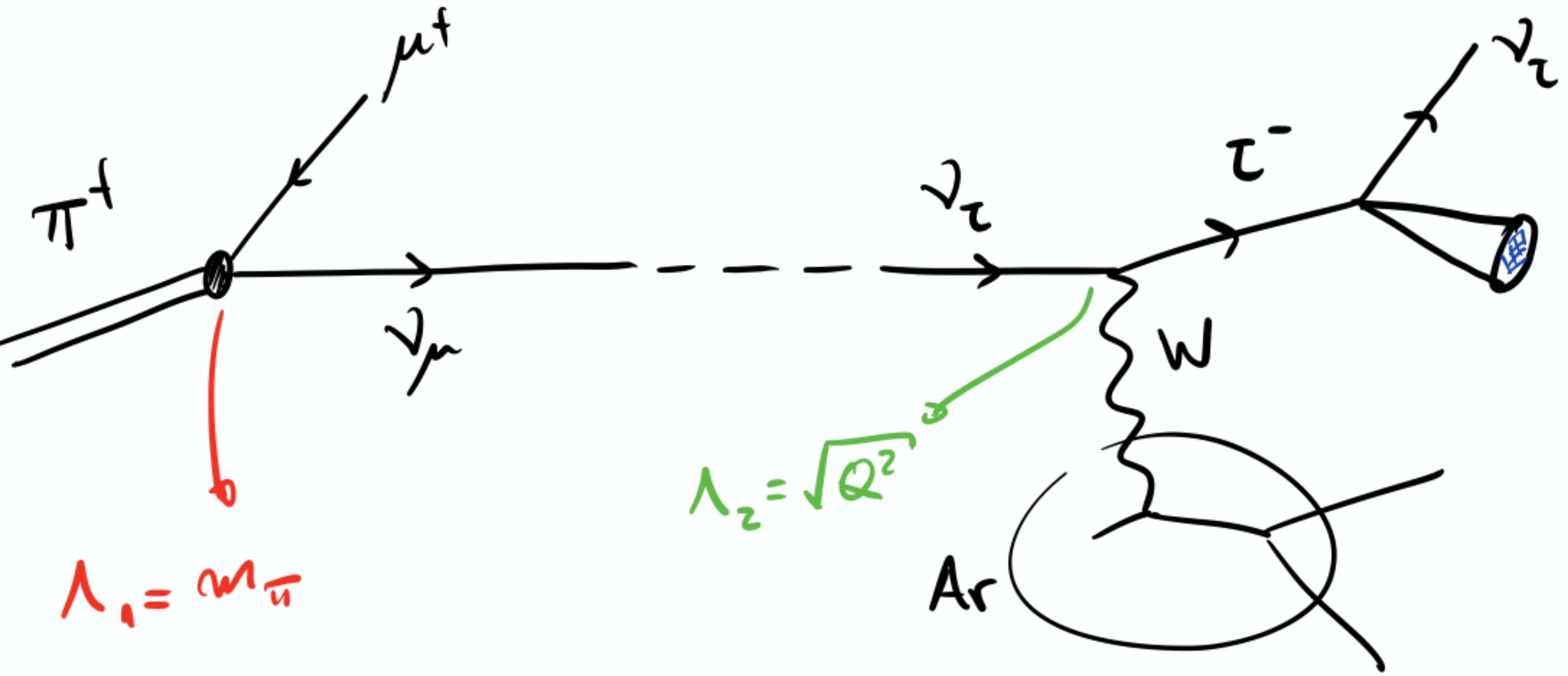

Standard case

$$\mathcal{A}(\nu_\mu \to \nu_\tau) = \langle \nu_\tau | \exp(-iHL) | \nu_\mu \rangle = \sum_i U_{\tau i} U^*_{\mu i} \exp\left(-\frac{i m_i^2 L}{2E}\right)$$

With E dependent effects

$$\mathcal{A}(\nu_\mu \to \nu_\tau) = \langle \nu_\tau, Q_2^2 | \exp(-iHL) | \nu_\mu, Q_1^2 \rangle = \sum_i U_{\tau i}(Q_2^2)\, U^*_{\mu i}(Q_1^2) \exp\left(-\frac{i m_i^2 L}{2E}\right)$$

This effect induces zero baseline ν_μ to ν_τ appearance, particularly at high energies

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